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Economic and policy uncertainty in climate change mitigation: The London Smart City case scenario

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ABSTRACT

Despite the overwhelming consensus within the scientific community concerning the causes and effects of climate change, decision-making processes often do not point out in the same direction. In order to effectively and satisfactorily tackle climate change, a legally and politically binding long-term policy architecture is needed. In practice, however, central governments and international policymakers have been unable to provide a successful policy architecture. Yet, city-level initiatives within the Smart City framework are a promising way to tackle climate change. An example of such a Smart City framework is the London Environment Strategy (LES). In this paper, we propose a zero mean reverting model for greenhouse gas emissions to quantitatively analyze its consistency with the 2050 Zero Carbon objectives. We consider different policy scenarios proposed in the LES and the forward-looking policy uncertainty embedded in different economic sectors, primarily domestic, industrial and commercial and transport. We find that, on average, only transport improves the historical greenhouse gas emissions trend, and most of this reduction comes from Smart Mobility and/or Smart Regulation programs focusing on the environment.

1. Introduction

"Why should we *not* maximize the welfare of this generation at the cost of posterity?" is a question that British economist Kenneth Boulding posed back in 1966. using the metaphor of the "cowboy economy" and the "spaceman economy," Boulding illustrated the difference between open and closed economies — see Boulding (1966). In the former, individuals are biased toward consumption and production. While in the latter, consumption and production are reduced with the purpose of maintaining a sustainable economy. Half a century later, Boulding's essay remains relevant particularly in the realm of climate change. Yet the question remains: how can we transition from a "cowboy economy" to a "spaceman economy"?

For such a change to occur, economic principles different from those of the past are needed. Concerning climate change, we have witnessed international initiatives such as the Kyoto protocol and the Paris Agreement aimed at lowering planet-warming greenhouse gas emissions. Yet, current environmental policies are unable to limit global warming to less than 2 °C — see Rogelj et al. (2016). Since economic and social factors play a critical role in defining the scope and the extent of climate change policies over time, the effectiveness of climate change initiatives remain sensitive to both economic and social factors. For example, policymakers tend to neglect environmental policies in periods of economic and social distress. In order to effectively and successfully respond to climate change, a legally and politically binding long-term policy architecture is needed. In other words, this policy architecture should carry less legal and political risk. Within the Smart City framework projects like the London Environment Strategy (LES) have turned out to be an efficient mechanism to mitigate the most severe effects of climate change because they carry less political and legal risk than other existing environmental measures.

Given the characteristics and scope of the London Environment Strategy (LES), it is considered as one of the most ambitious Smart City projects around the globe. As a result, we use this environmental strategy to create and simulate a zero-mean reverting model for the greenhouse gas emissions targets laid out in the 2050 Zero Carbon goals. Due to the uncertainty associated with climate change policies, we account for policy uncertainty through different simulation scenarios. We quantitatively analyze the consistency of our model results with the 2050 Zero Carbon goals and find that, on average, only the Transport sector improves the historical greenhouse gas emissions trend. And, most of the reduction in greenhouse gas emissions comes from Smart Mobility/Smart Environment Policies. These findings suggest that policymakers should invest more resources in further

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developing and supporting Smart Environmental Policies.

With this paper, we seek to contribute to the ongoing and rather recent debate on the role of Smart Cities in leading action against climate change – see Rosenzweig et al. (2010). As the London Environment Strategy becomes a model initiative, it is important to understand the extent to which Smart City initiatives may tackle climate change. Hence, the findings from our analyses can be useful for policymakers when drafting such policies and kicking off Smart City initiatives like the London Environment Strategy.

The rest of the paper is organized as follows. Section 2 describes the role of Smart Cities in achieving sustainable urban growth. Section 3 introduces the relationship between climate change, policy uncertainty and Smart Cities. Section 4 presents the case of the London Environment Strategy, the mean reverting greenhouse gas model and the simulation analysis on greenhouse gas emissions for Domestic, Industrial and Commercial, and the Transport sectors. Section 5 concludes.

2. Sustainable urban growth through Smart Cities

A city is an ecosystem where a set of interconnected people interact not only with each other, but also with its infrastructure and the environment. Due to their geographical location, history or any other idiosyncratic peculiarity, cities develop features that distinctively differentiate them. More interestingly, cities cannot be regarded as static systems because they change and adapt over time. For instance, cities or urban areas[1] are growing at an unprecedented rate in comparison to rural areas. In fact, global urban population exceeded global rural population for the very first time in 2007, and forecasts indicate that 70% of the population will live in urban areas by 2050.

In order to understand how cities have developed throughout the world, we delve deeper into the population growth patterns in urban vs. non-urban areas. Fig. 1 shows the historical evolution of urban population as a percentage of the total population for each of seven world regions: (1) Europe and Central Asia, (2) Latin America and the Caribbean, (3) the Middle East and North Africa, (4) North America, (5) East Asia and the Pacific, (6) South Asia, and (7) Sub-Saharan Africa. As it can be seen, population shifts to urban areas is a global trend with developing regions like Latin America and the Caribbean, and East Asia and the Pacific having higher urban growth rates than developed regions like North America, and Europe and Central Asia. While in 1960 only North America, and Europe and Central Asia had more populated urban that rural areas, by 2015 Latin America and the Caribbean, and the Middle East and North Africa experienced an urban population growth resulting in all four regions having more than 50% of their population concentrated in urban areas. As a whole, global urban population exceeded global rural population for the very first time in 2007. And, forecasts indicate that 70% of the population will live in urban areas by the year 2050. According to the United Nations' World Urbanization Prospects 2014, more than half of the world's population already lives in cities (United Nations, 2014). But how has population changed in densely populated urban areas? Fig. 2 shows the percentage of total population living in urban agglomerations of more than one million inhabitants. Also for these densely populated areas, the percentage of inhabitants has been steadily increasing since 1960. Due to the major increase in population in urban areas, it is projected that 41 mega-cities will house at least 10 million inhabitants each by 2030. With these urban population growth rates, cities have not been able to successfully adapt accordingly. For example, cities have not been able to develop adequate infrastructures and/or ways to deal with the negative environmental consequences that population growth may bring to cities.

In order to cope with the environmental byproducts of social change through population growth, awareness of the urban environment has increased, and the interaction of the environment with its inhabitants has been enhanced through Smart City projects. Through these projects, cities are able to profit from innovation and technological advances to improve the quality of life of their inhabitants. Similar to the "spaceman economy," Smart Cities partially focus on the efficient use of scarce resources to maintain a sustainable economy. For example, Caragliu et al. (2011) define a Smart City as a hub where limited financial resources are used to promote "sustainable economic growth and a high quality of life with a wise management of natural resources through participatory governance." While Caragliu et al. (2011) emphasize the role of financial resources in Smart Cities, limited resources can also be non-financial. Barrionuevo et al. (2012) and Bakici et al. (2012) define a Smart City as a space where all limited resources including technology are used "in an intelligent and coordinated manner" that "connects people, information and city elements [...] in order to create a sustainable, greener city, competitive and innovative commerce, and an increased life quality." For an in-depth literature review including the definition of Smart Cities, see Albino et al. (2015) and Bibri and Krogstie (2017).

For Smart Cities to develop not only capital, technological and human resources are needed; equally important, time has to be invested to develop and to achieve the desired targets from such initiatives. But since most environmental policies have a long-term plan, the longer the time horizon of the project the less utility it will offer thus making it less attractive for continuity. From an inter-generational *resourcist view*, later generations should not be left worse off (Page, 1999). However, just like any other inter-generational problem, a strictly positive inter-temporal discounting factor is expected to play a role in the execution of Smart City plans. That is, evaluating the payoff of projects having effects spreading over hundreds of years may conceptualize the project as something that does not matter (Weitzman, 1998).

In addition to time, economic fluctuations — growth, recession, stagnation — play a role in the importance Smart City projects may receive. In other words, the utility obtained from such Smart City projects changes with respect to both time and economic conditions. In other words, inter-temporal discounting strongly influences the extent to which Smart City projects are perceived as important thus strongly influencing the long-term success of a Smart City strategy. A key element in traditional policy analysis considers the effects of inter-temporal discounting and both the economic and social conditions over the policy-making process, and Smart City plans should not be an exception. In this regard, it is well established that in times of economic prosperity unemployment rate decreases, salaries tend to increase, and necessities are mostly satisfied and fulfilled. This reduces the time-discounting rate and increases the utility of future or long-term endeavors, such as sustainability and environmental initiatives. However, in times of economic distress basic economic and social indicators tend to worsen. Similarly, in times of social distress, individuals tend to prioritize short-term goals and certain necessities. In traditional policy analysis, this short-term prioritization is reflected as an increase in the inter-temporal discounting rate "reducing the relevance of posterity to almost insignificant" (Boulding, 1966). Periods of economic and social distress are thus particularly important for long-term policies, like those concerning climate change. Such distress perturbs the unstable equilibrium between economic, political, and social forces, provoking an uncertainty scenario where long-term policies are neglected. Consequently, Smart City policy architectures may be jeopardized along with the environmental sustainability of future generations. In this regard, periods of economic and social distress create certain barriers to the development and execution of environmental policies.

3. Climate change and policy uncertainty

A byproduct of population growth in urban areas concerns the environment. Figs. 3 and 4 depict the historical CO_2 per capita and the total greenhouse gas emissions between 1960 and 2014. North

[1] We take the freedom to use the terms cities and urban areas indistinctively.

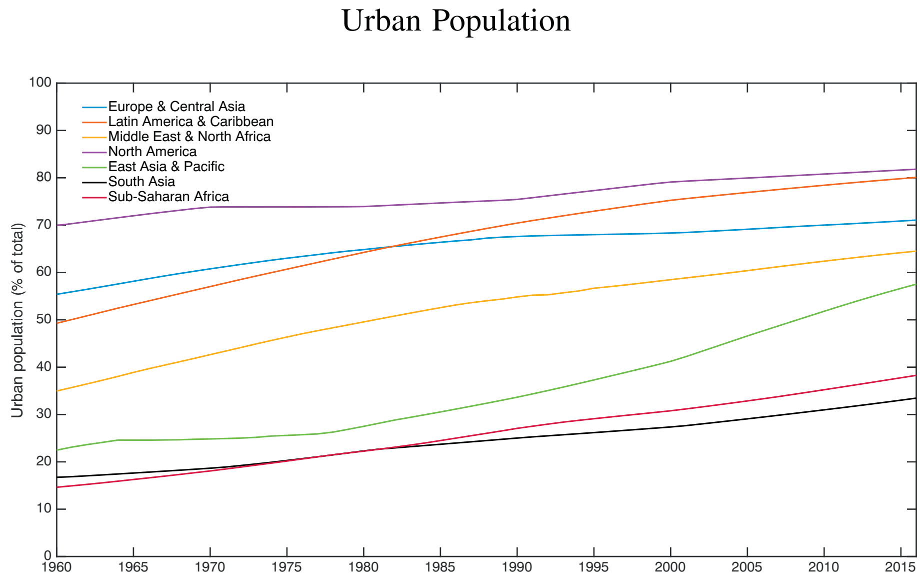

Fig. 1. This figure presents the evolution of urban population as a percentage of total population for each of seven world regions between 1960 and 2016. Source: Source: World Bank database.

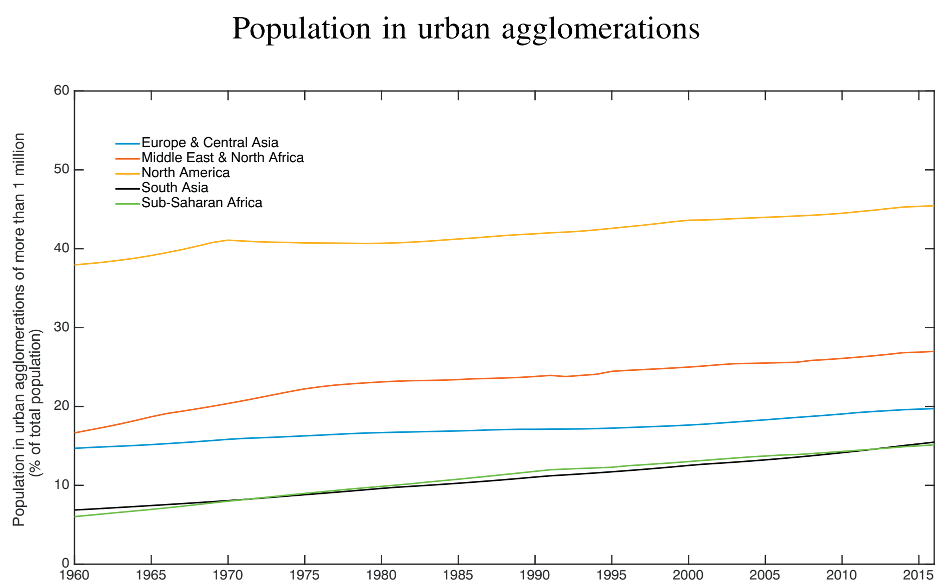

Fig. 2. This figure presents the percentage of the total population living in urban agglomerations of more than 1 million from 1960 to 2016 and by regions. Source: Source: World Bank database.

America, the region with the largest urban population, also happens to have the largest CO_2 emissions per capita (see Fig. 3). Similarly, the East Asia and the Pacific region which has experienced the largest urban population growth also has had the largest growth in CO_2 emissions per capita and total greenhouse gas emissions, see Figs. 3 and 4. But what is the current state of affairs concerning climate change, and policy making?

Despite the overwhelming consensus within the scientific community concerning the causes and effects of climate change, decision making often does not point out in the same direction. Just to mention one example, the Trump administration announced on June 2017 that the United States would withdraw from the 2015 Paris Agreement[2] after claiming that it undermined the US economy. Within the United Nations Framework Convention on Climate Change (UNFCCC), the 2015 Paris Agreement is probably one of the most world-wide comprehensive agreements to keeping global temperature rise well below 2 ° C by lowering greenhouse gas emissions. The UNFCCC signatory countries are committed to reduce greenhouse gas emissions through a set of climate-related actions known as the Intended Nationally Determined Contributions (INDCs).

While the Paris Agreement is a significant international step to manage climate change, it remains insufficient for achieving a satisfactory solution to most climate change issues. Existing research by Rogelj et al. (2016) has shown that while the INDCs do lower greenhouse gas emissions, the median warming is expected to range between 2.6 and 3.1 ° C by 2100. And these increases in global warming were estimated before the US withdrawal from the Paris Agreement. Having one of the largest producers of CO_2 and greenhouse emissions pulling out from the Paris Agreement will further undermine the effectiveness of this initiative. Hence, the success of this agreement heavily depends

[2] The United States is second largest polluter in the world with about 5414 million metric tons of CO_2 emissions per year.

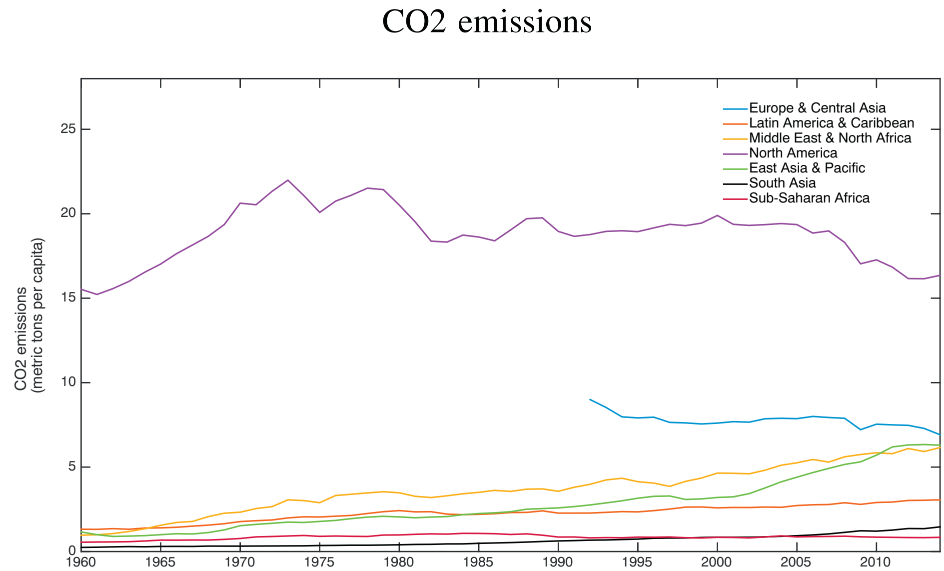

Fig. 3. This figure presents the historical CO_2 emissions per capita from 1960 to 2014 by region.
Source: Source: World Bank database.

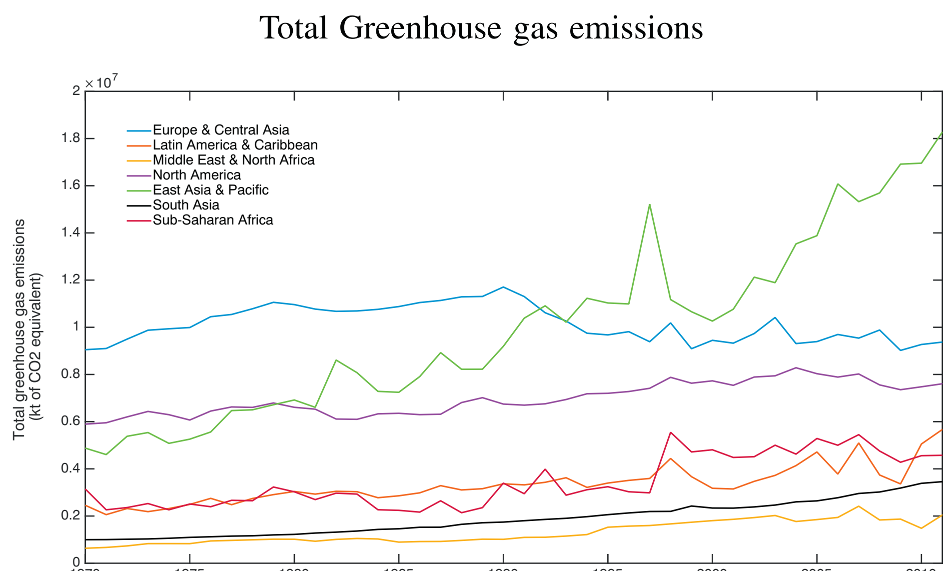

Fig. 4. This figure presents the historical total greenhouse gas emissions from 1960 to 2011.
Source: Source: World Bank database.

on the political ideology of current and future world leaders.

It seems that a more efficient, adequate, and potentially successful solution to tackling climate change would require an unprecedented international collaboration that goes well beyond the Paris Agreement. However, large international collaborations require large coordination efforts. In this regard, Victor (2007) proposes a "club" approach where a small club of countries would negotiate policies. With a small number of countries, the club scheme would allow for much finer tailoring of policy commitments. In practice, the European Union could be perceived as an example of such a club scheme with long-term plans. However, clubs like the European Union also face challenges. Brexit has threatened European Union-level policies after the United Kingdom voted on a referendum on June 23, 2016, to withdraw from the European Union.

Just as inter-temporal discounting plays a key role in traditional policy-making, political uncertainty and risk are relevant to designing and implementing policies of any kind and also to execute and preserve them over time. Figs. 5 and 6 present the economic policy uncertainty evolution between 1997 and 2017 for different regions: Global, Europe, United States (U.S.) and China, and for a set of European countries: France, Germany, Italy and Spain, respectively. At the European level, one can observe a pronounced peak in the economic policy uncertainty indicator of the U.K. in June 2016 as a result of Brexit. Tables 1 and 2 show the linear correlation among the economic policy uncertainty indexes for the global, Europe, U.S. and China indices, and France, Germany, Italy and Spain's indices, respectively. Overall, the economic policy uncertainty indices from the U.S., Europe and China display a high correlation. This is by no means surprising given the increasing globalization. Within Europe we observe high correlation among countries. However, despite the political instability in southern

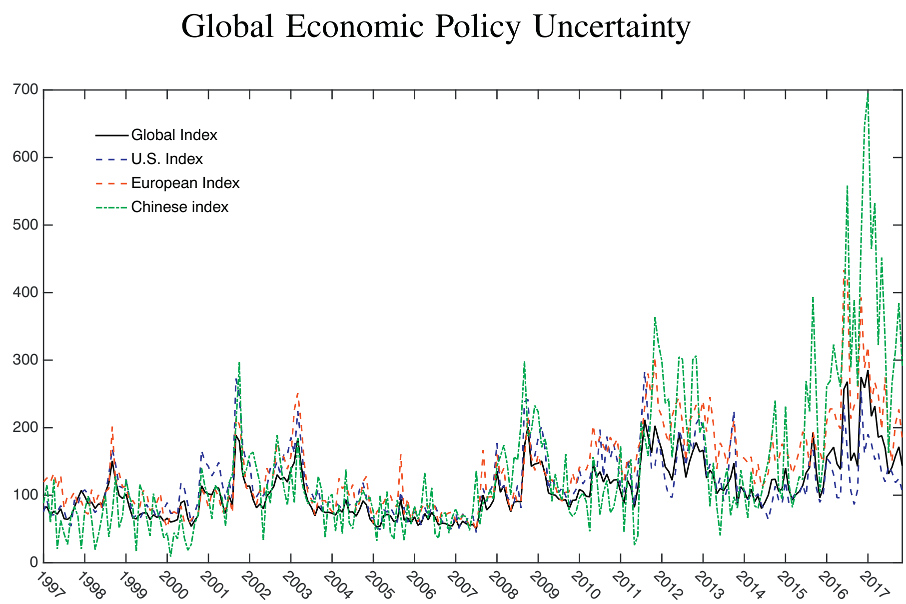

Fig. 5. The figure shows the global, European, US, and Chinese policy-related economic uncertainty Index from 1997 to 2017.
Source: Source: http://www.policyuncertainty.com.

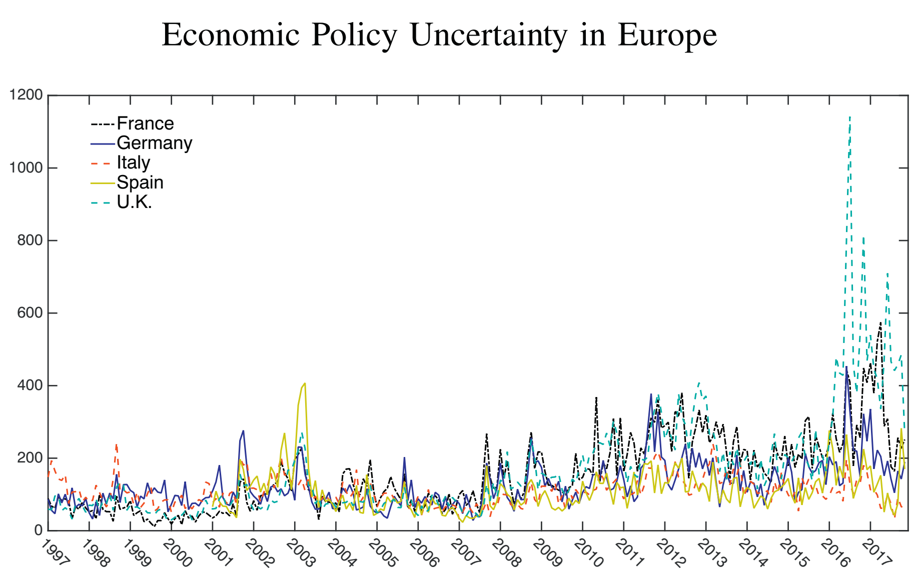

Fig. 6. The figure shows the French, German, Italian, Spanish, and British policy-related economic uncertainty Index from 1997 to 2017.
Source: Source: http://www.policyuncertainty.com.

Table 1
Global economic policy uncertainty correlation. This table shows the correlation between the global, European, U.S., and Chinese policy-related economic uncertainty Index from 1997 to 2017.
Source: Source: http://www.policyuncertainty.com.

	Global	Europe	U.S.	China
Global	1	0.9208	0.8197	0.8602
Europe		1	0.6945	0.7593
U.S.			1	0.5138
China				1

Table 2
Economic policy uncertainty correlation in Europe. This table shows the correlation between the French, German, Italian, Spanish, and British policy-related economic uncertainty Index from 1997 to 2017.
Source: Source: http://www.policyuncertainty.com.

	France	Germany	Italy	Spain	U.K.
France	1	0.7201	0.4103	0.4679	0.7795
Germany		1	0.4461	0.5599	0.7063
Italy			1	0.4609	0.3099
Spain				1	0.4053
U.K.					1

European countries, Italy and Spain exhibit lower correlation levels.

Even if policymakers successfully solve for inter-temporal discounting in environmental policy making, the potential success of long-term international partnerships concerning environmental initiatives are still exposed to political risk. Hence, international agreements on climate change should be not only legally but also politically binding. That is, political enforceability is an essential requirement in agreements with long time horizons because it is the only way to secure their applicability and protect them from changes in political leadership.

Despite the ideal approach for tackling climate change may be a global response, in reality central governments and international policymakers are unable to provide a coordinated and lasting response to such important issues. In fact, most strategies, policies, and funding mechanisms concerning climate change have been taken at the cities level (Hughes et al., 2018). With cities playing a key role in climate change, they have also emerged as the first responders in adapting to and mitigating climate change (Rosenzweig et al., 2010) some of them via the Smart City framework.

4. Smart City case: London

Within the U.K., London has been severely affected by political, economic, and social uncertainty as a result of Brexit. Although the Brexit negotiations are still ongoing and the outcome is far from clear, London is destined to become a mega-city housing 9,84 and 10,11 million inhabitants by 2031 and 2036, respectively.[3] As already discussed in Section 2, population growth brings environmental challenges.

While London has managed to reduce greenhouse gas emissions from 6% in 2012 to 16% in 2014 — with respect to 1990 levels — forecasts predict only a 25% reduction in greenhouse gas emissions by 2050. This predicted reduction in greenhouse gas emissions mainly stems from the expected growing population and if no further environmental policies — from the existing ones — are implemented. Consequently, current environmental conditions and the expected population growth indicate that existing environmental policies are insufficient to achieve the desirable reduction of greenhouse gases emission by 2050.

In this regard, the Mayor of London — Saduq Khan — has launched the London Environmental Strategy[4]. Given the characteristics of London, the London Environment Strategy—roadmap to zero carbon by 2050—is, probably, one of the most ambitious Smart City projects. The climate change section can be summarized enumerating its three main objectives: i) to reduce emissions in homes and workplaces and tackling fuel poverty, ii) to develop clean and smart, integrated energy systems focused on local and renewable energy sources, and iii) to develop a zero emissions transport network by 2050. The three objectives are perfectly in line within every Smart City framework and most of the proposed policies and projects are designed and managed by the city thus they are not fully dependent on governments and the political uncertainty they bring to environmental-led initiatives.

However, Smart City initiatives are not independent from International and National policies. As a matter of fact, most Smart City's goals and objectives need to be complemented and reinforced by further International and/or National-level actions. In addition, governments retain control over certain areas such as fiscal incentives thereby adding some political risk. In this regard, London's goal of reaching a zero carbon emissions goal is not exempted from political risk. Yet, Smart Cities appear to be a viable way in which environmental initiatives may be able to create a difference. In the next section, we will further explore how the London Environmental Strategy seeks to achieve its environmental goals through its Smart City framework.

4.1. Greenhouse gas mean reverting model

Let us assume that greenhouse gas emissions (GHG) over time follow a stochastic differential equation (SDE) describing a mean-reverting process. That is an Ornstein-Uhlenbeck process as follows:

$$d\mathrm{GHG}_t = \kappa(\alpha - \mathrm{GHG}_t)dt + \sigma dW_t \tag{1}$$

where κ, α, and σ are constant parameters describing the speed of mean reversion or mean reversion rate, the long-term mean level, and the process volatility, respectively; and W_t is a standard Wiener process. Considering the change of variable $g(\mathrm{GHG}_t,t) = \mathrm{GHG}_t e^{\kappa t}$, the SDE has the following solution:

$$\mathrm{GHG}_s = e^{-\kappa(s-t)}\mathrm{GHG}_t + (1 - e^{-\kappa(s-t)})\alpha + \sigma\int_t^s e^{-\kappa(s-u)}dW_u \tag{2}$$

Clearly, under this specification GHG_t follows a normal distribution, where its first two conditional statistical moments are given by

$$E[\mathrm{GHG}_s|\mathscr{F}_t] = e^{-\kappa(s-t)}\mathrm{GHG}_t + (1 - e^{-\kappa(s-t)})\alpha$$

$$V[\mathrm{GHG}_s|\mathscr{F}_t] = V\left[\sigma\int_t^s e^{-\kappa(s-u)}dW_u\right] = \sigma^2\int_t^s e^{-2\kappa(s-u)}du \tag{3}$$

$$= \frac{\sigma^2}{2\kappa}(1 - e^{-2\kappa(s-t)}) \tag{4}$$

where $\mathscr{F}_t$ represents a filtration and, in calculating the variance, it has been applied the isometry property of the stochastic integral. Since the GHG time-series are provided on an annual basis, we discretize Eq. (2) through a straightforward application of Euler discretization rendering:

$$\mathrm{GHG}_{t+\Delta t} = e^{-\kappa\Delta t}\mathrm{GHG}_t + (1 - e^{-\kappa\Delta t})\alpha + \sigma\sqrt{\frac{1 - e^{-2\kappa\Delta t}}{2\kappa}}\,\epsilon \tag{5}$$

where $\Delta t = 1$ year and $\epsilon \sim N_{0,1}$.

The relationship between consecutive observations is linear. Hence we can simplify Eq. (5) as follows:

$$\mathrm{GHG}_{t+\Delta t} = a + b\cdot\mathrm{GHG}_t + \varepsilon \tag{6}$$

with ε is independent and identically distributed. Note that, if the long-term greenhouse gas emissions' target is equal zero, it corresponds to a zero mean reverting process. In this case, $\alpha = 0$ and a vanishes. Then, we can easily interpret the speed of mean reversion κ with the concept of half-life:

$$T = \frac{\ln 2}{\kappa} \tag{7}$$

where T represents the average time the process takes to revert half-way back to the mean.

The London Energy and Greenhouse Gas Inventory (LEGGI) provides data on greenhouse gas emissions from Domestic, Industrial and Commercial and Transport operations sectors within the Greater London area between 2010 to 2014. We use this data to obtain estimates for the structural parameters in Eq. (6) and calibrate the model. The estimates are obtained by solving a linear least square problem. After conducting the estimation, we can easily recover the value of the parameters in Eq. (5). To get a better understanding of the fit of our estimates, Fig. 7 plots the dependent and independent variables in Eq. (6) along with their linear fit.

Panel A in Table 3 presents the calibration results from the linear least squares estimation. We report all estimates for each of the three sectors: Domestic, Industrial and Commercial and Transport.[5] Our results show that with a κ value equal to 0.0327 the Industrial and Commercial sector has the highest speed of mean reversion. That is, the Industrial and Commercial sector has the highest convergence rate toward a zero emissions level. Considering that the greenhouse gas emissions level in 2015 was equal to 15.57 $\mathrm{MtCO_2e}$, an emissions level equal to 7.78 $\mathrm{MtCO_2e}$ would be expected by 2036 assuming that the current trend in greenhouse gas emissions remains unchanged. Even though the Industrial and Commercial sector has the highest convergence rate, its estimated volatility equal to 1.3128 and its current

[3] According to the Greater London Authority (GLA).

[4] Draft version published online on November 2017. The final London Environment Strategy will be published in 2018. https://www.london.gov.U.K.

[5] In every case, a zero mean reverting process is assumed. We also conducted a robustness check where a standard Ornstein-Uhlenbeck process is assumed and the results confirmed the null hypothesis that $\alpha = 0$.

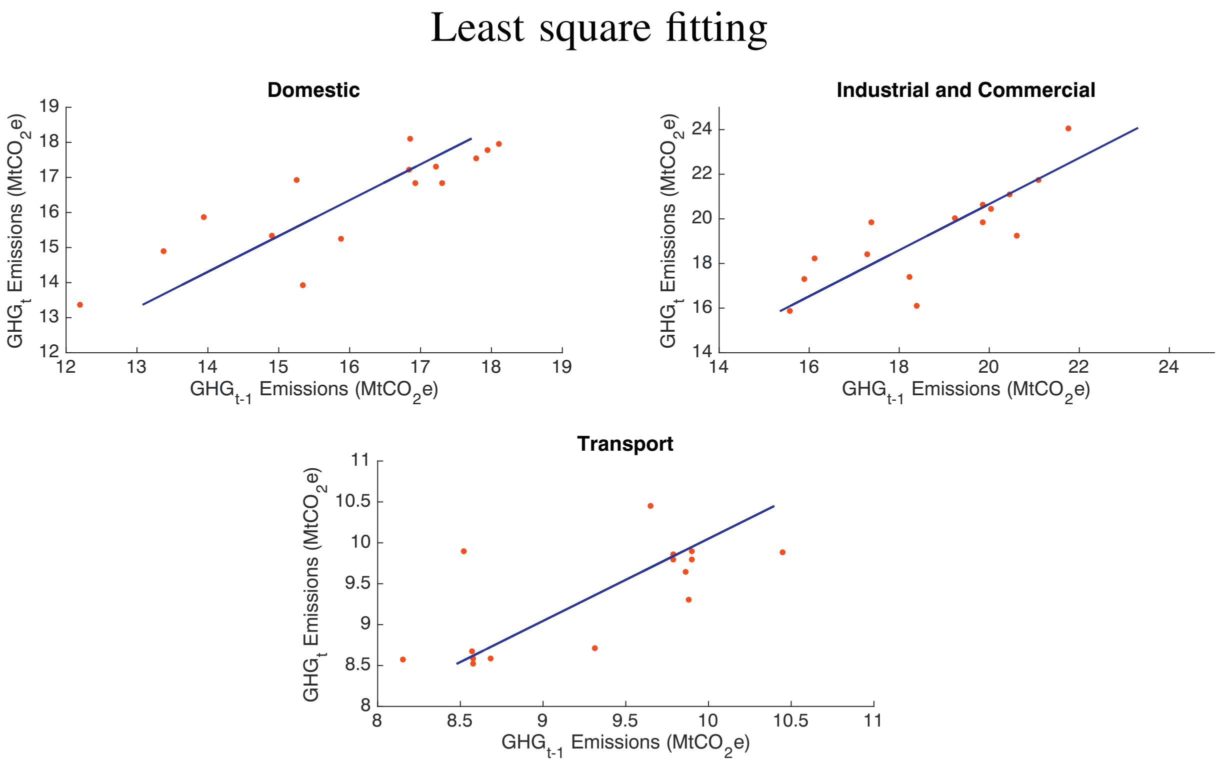

Fig. 7. This figure presents a scatterplot of the variables along with the least squares fitted line for Domestic, Industrial and Commercial, and Transport sectors.

Table 3
This table presents the estimated parameters from Eq. (5). *T*-years represents the half-life, κ the speed of mean reversion, σ the process volatility, and R^2 the coefficient of determination. All estimates are significant at the 0.01 level.

	Domestic	Industrial & commercial	Transport
Panel A: Model calibration			
κ	0.0218	0.0327	0.0050
σ	0.9773	1.3128	0.5210
T-years	32	21	139
R^2	0.7078	0.5750	0.4727
Panel B: Inter-sectoral Pearson correlations			
Domestic	1	0.8931	0.7381
Industrial & commercial		1	0.4707
Transport			1

emissions levels are also the highest thus providing more dispersion around the expected value. The Transport sector has the lowest convergence rate as the value for *T*-years in Table 3 shows. According to the estimated value for *T*-years, it would take 139 years to reach the emission level of 4.07 $MtCO_2e$, assuming the current trend in greenhouse gas emissions. The magnitude of this effect is significant since the transport sector accounts for 20% of London's greenhouse gas emissions. In particular, considering inter-temporal discounting effects, this slow effect might discourage future or further policies on Smart Mobility. Finally, the Domestic sector presents an intermediate level which might lead to an expected emission level of 6.09 $MtCO_2e$ in 2047, also far from the 2050 zero level objective.

4.2. Simulation analysis

In this section we quantitatively analyze a set of policies in the London Environmental Strategy, their consistency with the 2050 Zero Carbon objective, and the effect of policy uncertainty. To this end, we perform a Monte Carlo Simulation (MCS), where first we select the combination of policies that generates the best — Optimistic — and worst — Pessimistic — case scenarios for the Domestic, Industrial and Commercial and Transport sectors according to the London Zero Carbon Pathways Tool.[6] The Optimistic(Pessimistic) scenario will delimit the lower(upper) boundary in the simulation.[7] We then use the correlation coefficients reported on Panel B in Table 3 to compute correlated random numbers using Cholesky decomposition and perform 10,000 MCS for each of the three sectors.

We illustrate the results from our MCS in Fig. 8. The solid blue line that stretches from 2000 through 2015 represents historical greenhouse gas emissions. Whereas the series represented in dotted lines represent the simulated greenhouse gas emissions following different scenarios: pessimistic scenario (navy blue series), optimistic scenario (black series), the greenhouse gas emissions assuming a continuation of the historical trend (light blue series), and the greenhouse gas emissions assuming considering the average of the simulated paths (red series).

Table 4 presents the numerical results of the simulation (MCS) and both case scenarios (Optimistic and Pessimistic) for all three sectors: Domestic, Industrial and Commercial and Transport. The MCS presents some interesting results. On average only Transport improves the historical trend: the half-life time significantly drops by 75.54% from the 139 years reported in Table 3 to 34 years. These results are consistent with the Smart Mobility/Smart Environment Policies and objectives proposed in the London Environmental Strategy which include the following:

[6] Within the London Environmental Strategy, the GLA provides the London Zero Carbon Pathways Tool (https://maps.london.gov.U.K./zerocarbon). This tool provides a detailed pathway scenario analysis toward the 2050 Zero Carbon objective. Considering seven different dimensions, each scenario explores the impact of different policies and objectives both at a city and national level.

[7] Note that, under the posited model specification, GHG_t follows a normal distribution with mean and variance as in Eqs. (3) and (4), where the unconditional upper(lower) boundary of the distribution is $\infty(-\infty)$.

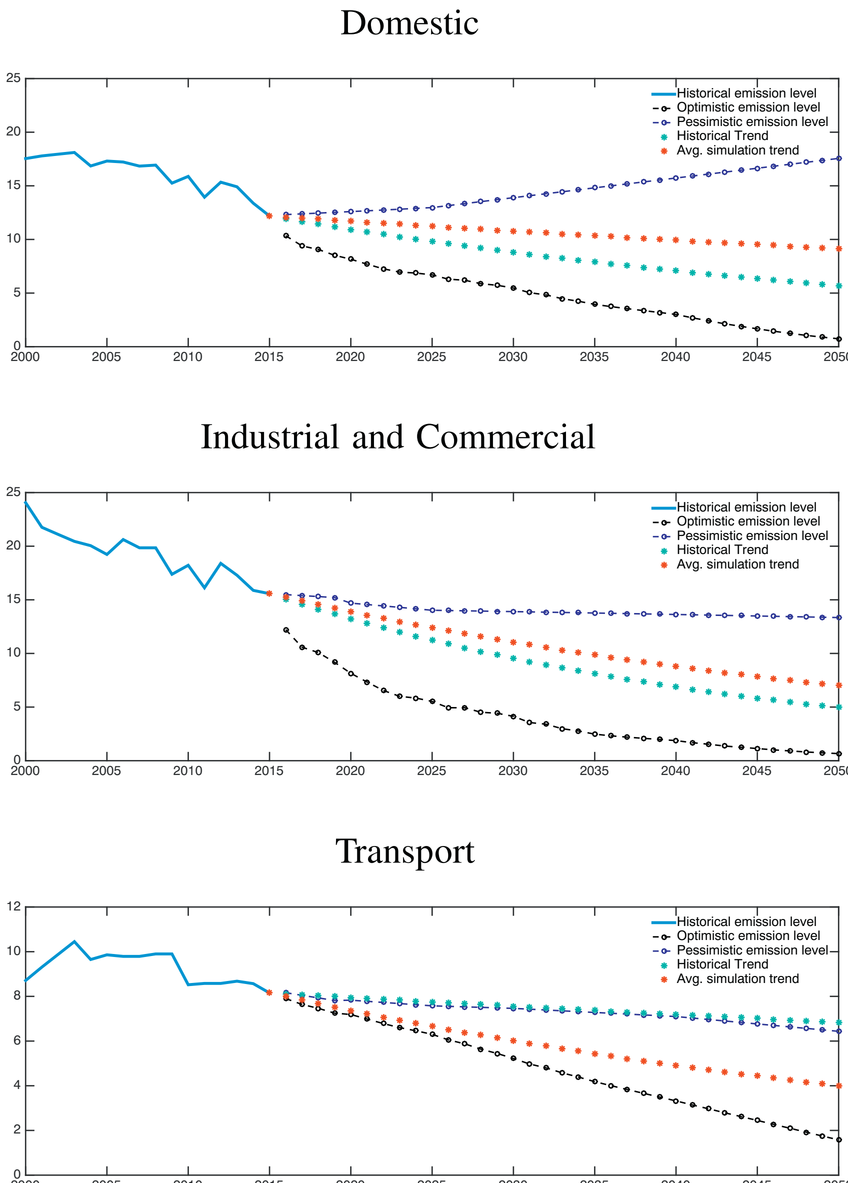

Fig. 8. This figure presents the MCS, the historical greenhouse gas emissions between 2000 to 2015, the Optimistic(Pessimistic) case scenario, the evolution of greenhouse gas emissions assuming a continuation of the historical trend, and the evolution of greenhouse gas emissions considering the average of the simulated paths for the Domestic, Industrial and Commercial, and Transport sectors. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

- 2019 Central London Ultra Low Emission Zone (ULEZ).
- 2025 GLA car fleet zero emission capable.
- 2037 all bus fleet zero emission.
- 2040 the majority of public transport will be zero emission.
- 2050 zero emissions from all transport.

In addition to the average improvement from the historical trend, the MCS shows a rather lower level of uncertainty in the Transport sector than in the other two sectors. The level of uncertainty is reflected in the volatility parameter, σ. In the Transport sector, an uncertainty level of $\sigma = 0.4136$ is significantly lower than the uncertainty levels in Domestic and Industrial and Commercial sector of $\sigma = 0.6813$ and $\sigma = 0.6869$, respectively. The lower uncertainty level might be well explained by the policy-making degree of competence at the city level. The Domestic sector average worsening arises from the extremely poor Pessimistic scenario, in fact, it is the only case with an upward sloping trajectory.

The Optimistic case scenario is quite in line with the 2050 Zero Carbon pathway as it is consistent with a zero mean reverting process, that is $\alpha = 0$. Moreover, there is a significant increase in the speed of mean reversion in the three sectors in comparison to those reported in Table 3. Overall, in comparison to the half-life time values reported in Table 3, the half-life time under the Optimistic scenario time reduces by 19.5, 13.5, and 119 years for the Domestic, Industrial and Commercial, and Transport sectors, respectively. While the Transport sector still has the lowest convergence rate among all three sectors, its improvement is drastic considering that the current trend in the reduction of greenhouse gas emissions indicates a half-life time of 139 years.

On the other hand, the Pessimistic case scenario presents some model anomalies. First, since $b > 1$ the Domestic sector is not consistent with a mean reverting process, therefore we can not find estimates for α nor κ. Indeed, Fig. 8—upper graph - dotted blue line — visually shows that the Pessimistic case scenario presents a rather convex behavior pushing the value of greenhouse gas emissions in 2050 to levels close to

Table 4
This table presents the MCS results and the estimated parameters for both the Optimistic and Pessimistic case scenarios. T-years represents the half-life, κ the speed of mean reversion, σ the process volatility, and α represents the long-term mean reversion level of greenhouse gas emissions measured in $MtCO_2e$. a and b represent the intercept and slope in Eq. (6), respectively, and R^2 is the coefficient of determination. All estimates are significant at the 0.01 level.

	Domestic	Industrial & commercial	Transport
MCS			
κ	0.0082	0.0228	0.0203
σ	0.6813	0.6869	0.4136
T-years	84,5	30,5	34
Optimistic			
b	0.9467	0.9127	0.9656
a	0	0	0
stdv (ε)	0.1376	0.1897	0.0711
κ	0.0547	0.0913	0.0350
α	0	0	0
σ	0.1414	0.1984	0.0724
T-years	12,5	7,5	20
R^2	0.9971	0.9954	0.9986
Pessimistic			
b	1.0213	0.9065	0.9931
a	− 0.1544	1.2472	0
stdv (ε)	0.0359	0.0724	0.0278
κ	–	0.0982	0.0069
α	–	13.3356	0
σ	–	0.0759	0.0279
T-years	–	–	100,5
R^2	0.9995	0.9825	0.9959

those in 2000. In contrast, the Industrial and Commercial Pessimistic scenario is consistent with a mean reverting model. However, the long-term mean reversion level is 13.3356 $MtCO_2e$, a level slightly better than the 2015 level. The Transport Pessimistic scenario is consistent with a zero mean reverting process, and surprisingly similar to the historical trend evolution. It is encouraging and consistent with the Smart Mobility dimension since most transport policies are designed, implemented, and executed at the city level. Nevertheless, the Pessimistic scenario is still not consistent with the 2050 Zero Carbon objective since its half-life time is equal to 100 years.

5. Conclusion

Climate change is one of the most serious challenges that humanity faces in the XXI century. A policy-driven solution to prevent the most drastic effects of climate change requires a long-term policy architecture that is independent — without exceptions — of the ideological party of the incumbent and successive governments in power, i.e. no policy risk. In contrast to the unsuccessful attempts of central governments and international policymakers to provide a satisfactory global response, most actions oriented to mitigate the effects of climate change have been taken at the city level, most precisely within the Smart City framework.

While not fully exempted from policy risk, London has launched one of the most ambitious Smart City projects aiming at staving off the most drastic effects of climate change: the London Environment Strategy (LES)—roadmap to zero carbon by 2050. Considering different policy scenarios proposed in the LES, this paper proposes a zero mean reverting model for London's greenhouse gas emissions and quantitatively analyzes the consistency of the 2050 Zero Carbon objective and the forward looking policy uncertainty embedded in the Domestic, Industrial and Commercial, and Transport sectors.

Considering the 2000–2014 greenhouse gas emissions trend, the Industrial and Commercial sector has the highest convergence rate toward a zero emission level. If the current trend remains unchanged, the expected greenhouse gas emissions level would reach 7.78 $MtCO_2e$ by 2036. Although the Industrial and Commercial sector has the lowest half-life with 21 years, it also has the highest volatility generating more dispersion around the expected value and thus more uncertainty around the achievement of long-term objectives concerning this sector. While accounting for 20% of London's greenhouse gas emissions, the Transport sector presents the lowest convergence rate with a half-life of 139 years according to the current reduction trend. This convergence rate is not in line with the 2050 Zero Carbon objective. The Domestic sector, on the other hand, presents an intermediate level with a half-life of 32 years, leading to an expected emissions level of 6.09 $MtCO_2e$ in 2047, again far from the 2050 zero level objective.

When conducting our simulation analysis, we find that only the Transport sector improves the historical trend by reducing the half-life time from 139 to 34 years. This result is consistent with the Smart Mobility and Smart Environment Policies and objectives proposed in the London Environmental Strategy. Moreover, the upper boundary is consistent with a zero mean reverting process, and surprisingly similar to the historical trend evolution. Inasmuch as it does not represent a worsening from the current trend, the Transport sector's worst case scenario is encouraging.

In addition, the Monte Carlo simulation also shows a rather lower level of uncertainty in the Transport sector than in the other two sectors. Transport reports a $\sigma = 0.4136$, significantly lower than $\sigma = 0.6813$ and $\sigma = 0.6869$ in the Domestic and Industrial and Commercial sector, respectively. This lower uncertainty level could be explained by the extent to which this sector is more manageable through city-level policy-making. Uncertainty is a key element in the effect of environmental policies. Nevertheless, as more initiatives to fight climate change emerge, this uncertainty level might decrease.

We propose to complement Smart City initiatives with further International and National-level policies that are both legally and politically binding in order to transition from a "cowboy economy" to a "spaceman" and hence sustainable economy. As such, the results from this paper can be further used by policymakers as a way to understand the feasibility of current environmental policies, including Smart City programs like the London Environment Strategy.

Appendix A

Table 5
This table presents the main policies defining the Optimistic case scenario.
Source: Source: http://maps.london.gov.U.K./zerocarbon.

Optimistic scenario		
Energy efficiency uptake	High uptake	Up to 50% of buildings upgraded by 2025, 100% 2050. Increased proportion of whole house retrofits
Heat pump uptake	High uptake	Up to two million heat pumps installed by 2050
Heat network deployment	High uptake	Tenfold increase in heat networks by 2025, connecting up to 650,000 homes to waste and environmental heat sources by 2050

(continued on next page)

Table 5 (*continued*)

Optimistic scenario		
PV deployment scenario	Ambition	Rapid uptake with up to 100,000 installations by 2025, increasing to 25% of all viable buildings by 2050
Electricity grid decarbonisation	National grid FES: 2°	–
Gas grid decarbonisation	Zero carbon gas grid	Future investment in zero carbon gas leads to widespread adoption. London's gas network is repurposed with a zero carbon gas (such as hydrogen) by 2050
Transport scenario	Near zero	High investment accelerates conversion of all road transport vehicles to zero emission by 2050

Table 6
This table presents the main policies defining the Pessimistic case scenario.
Source: Source: http://maps.london.gov.U.K./zerocarbon.

Pessimistic scenario		
Energy efficiency uptake	Low uptake	Up to 5% of buildings upgraded by 2025, 15% by 2050
Heat pump uptake	Low uptake	Up to 300,000 domestic heat pumps by 2050
Heat network deployment	No additional heat networks	–
PV deployment scenario	Business as usual	Steady uptake in line with recent deployment. Up to 20,000 installations by 2025, increasing to 10% of all viable buildings by 2050
Electricity grid decarbonisation	2015 factor unchanged	–
Gas grid decarbonisation	Natural gas	Gas grid remains largely consistent, with priority on decarbonisation of electricity only
Transport scenario	Baseline	Minimal uptake of electric vehicles beyond ultra low emission zone and GLA fleets. No increase in transport investment beyond current ambition

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